Fermi Gamma-ray Space Telescope: Highlights of the GeV Sky

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Because high-energy gamma rays can be produced by processes that also produce neutrinos, the gamma-ray survey of the sky by the *Fermi Gamma-ray Space Telescope* offers a view of potential targets for neutrino observations. Gamma-ray bursts, active galactic nuclei, and supernova remnants are all sites where hadronic, neutrino-producing interactions are plausible. Pulsars, pulsar wind nebulae, and binary sources are all phenomena that reveal leptonic particle acceleration through their gamma-ray emission. While important to gamma-ray astrophysics, such sources are of less interest to neutrino studies. This talk will present a broad overview of the constantly changing sky seen with the Large Area Telescope (LAT) on the *Fermi* spacecraft.

1. INTRODUCTION

High-energy gamma rays are primarily produced by interactions of energetic particles, some of which also involve neutrino production. Typical processes are inelastic nuclear collisions (pion production), inverse Compton scattering, curvature radiation, and synchrotron radiation. In addition, the Universe is mainly transparent to gamma rays with energies less than 20 GeV; therefore they can probe distant or obscured regions. These features give gamma-ray observations the potential to image regions of neutrino production. Conversely, neutrino observations of gamma-ray sources present the possibility of helping understand the physical processes taking place in these objects.

The *Fermi Gamma-ray Space Telescope* was launched on June 11, 2008. Since August, 2008, the *Fermi* Large Area Telescope [1], the principal instrument on the satellite, has been surveying the sky at energies from 20 MeV to more than 300 GeV, taking advantage of its huge field of view (2.4 sr) and the scanning mode of operation of the satellite to view the entire sky every three hours. The present paper reviews some highlights of results from the *Fermi* LAT, with emphasis on connections to potential astrophysical sources of neutrinos.

2. THE GEV SKY: AN OVERVIEW

Unlike the sky at visible wavelengths, the gamma-ray sky is strongly dominated by diffuse radiation originating in our Milky Way Galaxy, making the Galactic plane the most striking feature in any large-scale gamma-ray skymap. Although the diffuse Galactic gamma radiation is brightest along the plane, it is seen at all Galactic latitudes. This radiation is largely produced by cosmic-ray interactions with the interstellar gas and photon fields through the processes of inelastic nucleon scattering, bremsstrahlung, and inverse Compton scattering. Fig. 1 shows the Spectral Energy Distribution (SED) of this radiation in part of the sky, along with modeled components [2]. The largest contributor to this radiation is nucleon-nucleon collisions (basically cosmic ray protons and heavier nuclei hitting interstellar hydrogen nuclei) with subsequent decay of π^0 mesons into gamma rays in the *Fermi* LAT energy range. The LAT measurements do not confirm the unexpected excess in the few GeV energy range measured by EGRET on the *Compton Gamma Ray Observatory (CGRO)* compared to models.

The fact that pions are a principal source for these gamma rays immediately implies that there is a similar diffuse Galactic neutrino emission,

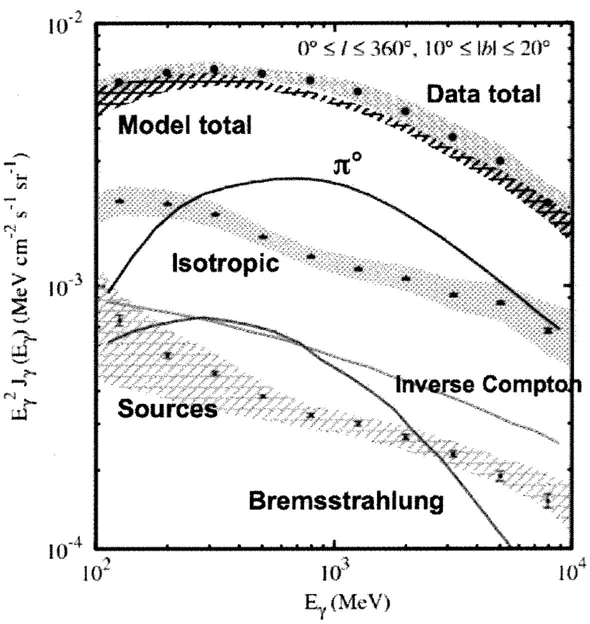

Figure 1. Spectral Energy Distribution (SED) of diffuse gamma radiation at intermediate Galactic latitudes. Overlaid are SEDs for the component processes of the diffuse emission. The primary component, shown by the heavier black line above the gray band, is decay of π^0 mesons [2].

and that the Galactic Plane is relatively bright as a source of GeV neutrinos. For both gamma rays and neutrinos, discrete sources are spatially localized excesses against this diffuse radiation. This diffuse gamma radiation also illustrates that other gamma-ray sources involving hadronic interactions are likely to be visible as neutrino sources.

The first *Fermi* LAT catalog [3] contains 1451 sources. At least two populations of sources are found: an isotropically distributed component, likely representing extragalactic sources, and a component clustered along the Galactic plane.

3. EXTRAGALACTIC GAMMA-RAY SOURCES

3.1. Gamma-ray Bursts (GRB)

The brightest and most distant gamma-ray sources do not appear in the LAT catalog. These are gamma-ray bursts, intense flashes lasting from a fraction of a second to many minutes. GRB are thought to result from particularly powerful core-collapse supernovae (long bursts) or from the mergers of neutron stars and black holes (short bursts). GRB results combine data from the LAT with those from the other *Fermi* instrument, the 8 keV to 40 MeV Gamma-ray Burst Monitor (GBM) [4], to cover more than 6 orders of magnitude in photon energies. Some of the *Fermi* results on GRB include:

- Both long (>2 sec) and short (<2 sec) GRBs have been seen by both instruments.
- Some bursts show high-energy emission afterglows in the LAT data, lasting for many minutes after the prompt emission, e.g. [5].
- *Fermi* observations of some bursts, under reasonable assumptions, put lower limits on bulk Lorentz factors in the source to be greater than 1000, e.g. [6].
- Some bursts have an extra spectral component compared to the standard Band model, e.g. [7].
- GRBs seen with the LAT and the GBM have placed constraints on some models of quantum gravity that predict Lorentz Invariance violation [8].

Because a supernova is a known astrophysical source of neutrinos, GRBs are undoubtedly producing large quantities of neutrinos. The problem for detection is one of distance, since most GRBs are at cosmological distances.

4. Active Galactic Nuclei (AGN)

More than half the *Fermi* LAT sources are associated with active galactic nuclei (AGNs), as shown in the first LAT catalog [3] and first LAT

AGN catalog [9]. In standard models, the energy that powers the activity of the galactic nucleus comes from material falling toward a supermassive black hole. In a process not fully understood, some of this energy emerges in a jet of high-energy particles that shoots away from the nucleus at relativistic speeds. The *Fermi* LAT sees primarily blazars, a subset of radio-loud AGNs for which the jet is pointed toward Earth.

Observations of correlated multiwavelength variability, in addition to confirming identifications for AGN gamma-ray sources, also help with modeling these jets. An example is PKS 1502+106, which exhibited a strong flare early in the mission [10]. The gamma-ray and X-ray flares seem correlated in this case, followed by a delayed flare seen in optical and ultraviolet light and a still later peak in the radio.

The SED of this blazar is complex, requiring multiple components that vary with time. Not all AGN flares show the same pattern of temporal and spectral variability, leading to one pivotal result for *Fermi* and multiwavelength studies: in most cases, simple models for blazar jets are inadequate. Models for AGNs do not even lead to a consensus on the nature of the particles carrying the energy. Although the gamma rays result directly from electron interactions, some or all of those electrons might be secondaries produced by hadronic interactions. If that were the case, then such AGNs might be seen as neutrino sources. Neutrino detection of a flaring AGN would then help confirm the particle content of the jet.

Spatially resolving AGNs at gamma-ray energies is generally not feasible. An exception is Centaurus A, a nearby radio galaxy. The giant radio lobes of Cen A, which span about 10° on the sky, are resolved in the LAT data [11]. Over half of the observed E>100 MeV LAT flux appears in the lobes. Such emission requires 0.1-1 TeV electrons in these lobes, either accelerated in the lobes or efficiently transported from the core of the galaxy.

5. Galaxies Dominated by Cosmic-Ray Interactions

Some galaxies not classed as AGNs are also seen as gamma-ray sources. Examples are normal galaxies, including the Milky Way, the Large Magellanic Cloud [12], the Small Magellanic Cloud [14], and starburst galaxies, such as M82 and NGC 253 [13]. GeV gamma rays in these galaxies come primarily from the interactions of cosmic ray hadrons and electrons with interstellar matter and photon fields. The gamma-ray luminosities of these normal and starburst galaxies show an approximately linear relationship with the product of the supernova rate and the total mass of gas in the galaxies [13]. Although this analysis is highly simplified, the trend supports the long-held expectation that supernovae are principal accelerators of cosmic rays (at least for hadrons).

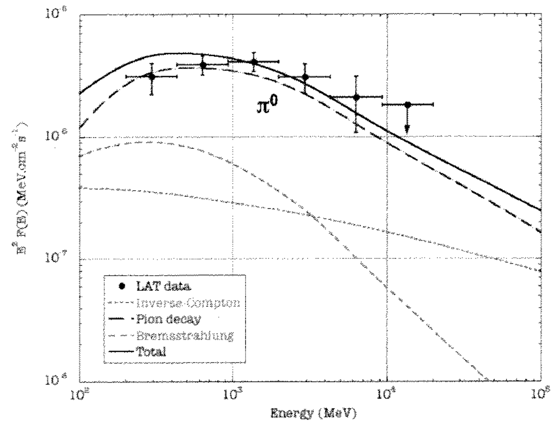

Figure 2. SED of gamma radiation from the Small Magellanic Cloud. Overlaid are SEDs for the component processes of the diffuse emission. The primary component is decay of π^0 mesons [14].

Figure 2 shows the measured spectrum from the Small Magellanic Cloud. The spectrum is modeled predominantly by π^0 decay, implying hadronic processes. As for the diffuse emission from our own Galaxy, the gamma radiation from such galaxies will be accompanied by a neutrino

component.

6. GALACTIC GAMMA-RAY SOURCES

6.1. Pulsars, Pulsar Wind Nebulae, and Binary Systems

Gamma-ray pulsars were the first class of sources identified at these energies. The first *Fermi* LAT pulsar catalog [15] contains 46 pulsars, and more continue to be identified. In addition to the young, radio-bright pulsars that were known from the *CGRO* era, LAT observations have added three new aspects to pulsar studies:

1. A significant number of millisecond pulsars are visible in the LAT data [16]. These old, recycled pulsars that have passed through a stage of being X-ray binaries are similar in their gamma-ray properties to the younger pulsars despite having much weaker surface magnetic fields and much faster rotation speeds.

2. Searches of gamma-ray arrival times from some bright unidentified LAT sources independent of any prior knowledge about pulsations revealed a new population of gamma-ray-selected pulsars [17], suggesting that the gamma-ray beams from at least some of these pulsars may be broader than the radio or X-ray beams.

3. In a multiwavelength effort, radio astronomers have discovered a number of new millisecond pulsars in error boxes of unidentified LAT sources [18], often assisted by source locations derived from X-ray observations.

In terms of neutrinos, these pulsars are not likely candidates. Models of pulsar physics strongly suggest that leptonic interactions are the favored mechanisms.

Much of the energy lost by pulsars as they slow down goes into the production of a pulsar wind, and the termination shock of this wind can accelerate particles (primarily electrons, although proton acceleration cannot be ruled out) and produce a pulsar wind nebula (PWN). The interacting PWN particles can then produce gamma rays. The LAT has seen several PWNe, including the Crab [19], where the LAT results connect to the observations from TeV Atmospheric Cherenkov telescopes, and the Vela X PWN [20], where the GeV and TeV emissions appear to originate from different electron populations.

Another class of gamma-ray sources seen by the LAT includes some high-mass X-ray binary (HMXB) systems, where the variation in the gamma-ray flux originates from the orbital motion of the system. One such system is Cygnus X-3, which has a neutron star or black hole in a 4.8-hour orbit around a massive star. The GeV gamma radiation clearly displays the orbital modulation [21], although the modulation is out of phase with the X-ray emission seen from the same system. The gamma-ray flux from Cyg X-3 is only visible when the low-energy X-ray flux is high and the high-energy X-ray flux is low. These HMXB systems are not well enough understood to know whether leptonic or hadronic particle production and interactions generate the gamma-ray flux.

6.2. Supernova Remnants (SNR)

Supernovae and their remnants have long been thought to be sites of cosmic-ray particle acceleration [22], and the collisions of these newly accelerated particles with the surrounding interstellar medium should then produce gamma rays (and neutrinos) by the same processes that produce the diffuse Galactic gamma radiation. The sensitivity and resolution of the *Fermi* LAT has now provided strong evidence in several cases for just such processes taking place.

One example is Supernova Remnant W44, which is spatially resolved by the LAT using the 2-10 GeV gamma rays that convert in the front part of the detector and have the best angular resolution [23]. The gamma-ray image resembles the shell structure seen with the Spitzer Infrared Array Camera [24], thought to represent dense clouds of shocked molecular hydrogen. These clouds form the targets for the cosmic rays accelerated in the SNR. The gamma-ray spectrum is consistent with π^0-decay, as seen in Figure 3, although it is possible to construct models in which the emission has a leptonic origin.

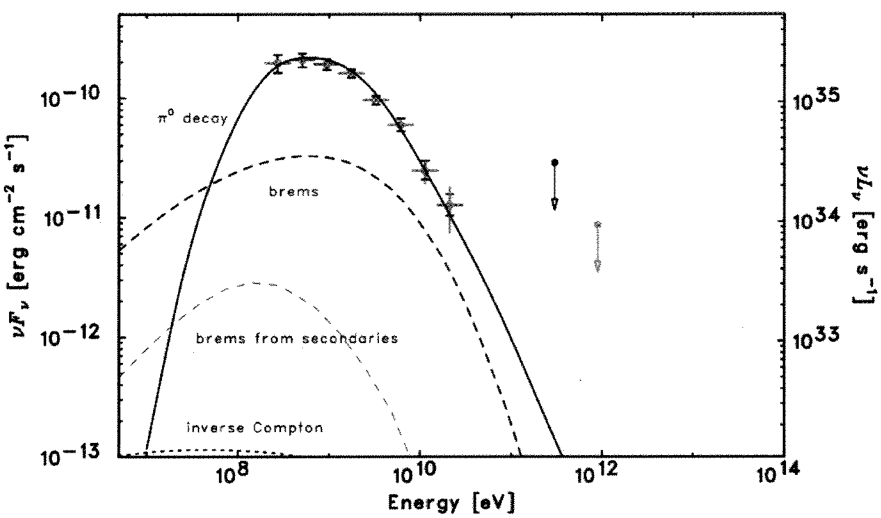

Figure 3. Spectral Energy Distribution of gamma-ray emission from SNR W44 [23]. The gamma-ray emission is modeled by a combination of π^0-decay (solid curve), bremsstrahlung (dashed curves), and Inverse Compton scattering (dotted curve). Upper limit data points above 10^{11} eV are from Whipple, HEGRA, and Milagro (left to right).

Another example is Supernova Remnant W51C, which is also spatially resolved by the LAT [25]. This SNR also contains shocked molecular clouds that could be targets for cosmic-ray interactions. Although both hadronic and leptonic models can explain the gamma-ray spectrum, the model parameters required by the gamma-ray observations predict different synchrotron radio spectra, and these appear most consistent with the π^0-decay-dominated gamma-ray calculation.

With the number of SNRs seen by the *Fermi* LAT growing, and with multiwavelength studies supporting an origin of the gamma rays in hadronic processes, the evidence is mounting for the long-conjectured hypothesis that SNRs are the source of the bulk of Galactic cosmic rays. The sample is still too small, however, to consider the case closed. If these models of the gamma radiation from SNRs are correct, they would also be neutrino sources. Seeing the neutrinos from SNRs would give the final proof of hadronic acceleration.

6.3. A Gamma-ray Nova

In March, 2010, the LAT data revealed a previously unseen flaring gamma-ray source in the Cygnus region of the sky [26], coincident in time and direction with an optical flare seen from the symbiotic binary system V407 Cygni [27]. The classical nova outburst from this red giant/white dwarf system was also seen in radio and X-rays, confirming its nonthermal nature. Particles accelerated in the expanding shell of the nova interact with the wind from the red giant and with the surrounding medium to produce the observed gamma radiation. The gamma-ray energy spectrum can be modeled as either π^0-decay or leptonic processes [26]. Although novae are far less powerful than supernovae, they are far more numerous. The LAT detection suggests that yet another class of objects can accelerate particles to cosmic-ray energies.

7. CONCLUSIONS

Gamma rays seen with the *Fermi Gamma-ray Space Telescope* are revealing sites of particle acceleration and interaction, ranging from distant gamma-ray bursts and active galactic nuclei to sources nearby in our own Galaxy. Many of these gamma-ray sources represent likely astrophysical neutrino sources.

The *Fermi* LAT results support, but have yet to prove definitively, the idea that supernovae are a primary source of cosmic rays. Pulsars and binary systems contribute to the cosmic-ray electron population. Novae are also potential cosmic-ray accelerators. Neutrino detections of such sources would provide firm evidence of hadronic interaction processes.

The *Fermi* mission is planned to continue at least three more years, and many discovery opportunities remain. All the *Fermi* gamma-ray data are public. The future of cooperative gamma-ray and neutrino studies is promising.

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